N92-22682

A LIGHTWEIGHT, HIGH STRENGTH DEXTEROUS MANIPULATOR FOR COMMERCIAL APPLICATIONS[1]

Neville I. Marzwell
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

Bruce M. Schena
Steve M. Cohan
Odetics, Inc.
1515 S. Manchester Avenue
Anaheim, CA 92802

ABSTRACT

This paper describes the concept, design, and features of a lightweight, high strength, modular robot manipulator being developed for space and commercial applications. The manipulator has seven fully active degrees of freedom and is fully operational in 1 G. Each of the seven joints incorporates a unique drivetrain design which provides zero backlash operation, is insensitive to wear, and is single fault-tolerant to motor or servo amplifier failure. Feedback sensors provide position, velocity, torque, and motor winding temperature information at each joint. This sensing system is also designed to be single fault-tolerant. The manipulator consists of five modules (not including gripper). These modules join via simple quick-disconnect couplings and self-mating connectors which allow rapid assembly/disassembly for reconfiguration, transport, or servicing. The manipulator is a completely enclosed assembly, with no exposed components or wires. Although the initial prototype will not be space qualified, the design is well-suited to meeting space qualification requirements. The control system provides dexterous motion by controlling the endpoint location and arm pose simultaneously. There is access to the control system at multiple functional task levels. Potential applications are discussed.

INTRODUCTION

Odetics Inc. is developing a new, high performance manipulator that will address new market opportunities space, defense, and commercial applications. Although these applications are embryonic and ill-defined, current manipulators clearly lack the general performance capabilities these tasks will require. Recent research in space telerobotics has made dexterity, fault tolerance, and safety requirements clearer [1-3]. The general approach guiding this design is to build an advanced manipulator which uses the best ideas from existing designs and has new features required for advanced applications in both the space and commercial arenas. Sophisticated software and control algorithms have been developed concurrently with the manipulator hardware, yielding an integrated system that is adaptable to many applications.

This applications class excludes most conventional industrial robots. In fact, there exists only a few commercially available manipulators that are potentially suitable for applications in dynamic, unstructured environments such as space and hazardous material handling. Some of these machines are hydraulically powered, such as the manipulators

1. This work was partially funded by NASA Small Business Innovation Research Contract NAS-1062

produced by Schilling Development[1], Kraft Telerobotics[2], and Sarcos [4]. While hydraulic manipulators have very good strength, speed, and size characteristics, they require hydraulic power support hardware with its inherent size and weight penalty. There is the additional danger of flammable hydraulic fluid leakage. These detriments make hydraulic manipulators unsuitable for some applications, such as those in space. Perhaps the only commercially available electric manipulators similar to the Dexterous Manipulator are those produced by Robotics Research, Inc. [5]. Some of the differences between the two manipulators are described in this paper.

DESIGN OBJECTIVES

New market applications will require autonomous and teleoperated manipulation in unstructured, dynamic environments. The capabilities of the manipulator system will ultimately determine the success or failure of these operations. As with most system developments, cost and development time requirements must balance performance and reliability goals. Since definitions of the tasks to be performed are still evolving, a reconfigurable system that could be easily adapted to various applications would be attractive. In particular, commercial applications could benefit from the reduced cost of reconfiguring the system for a new application, in contrast with developing special equipment, such as tooling, for each new use. The system should be configured to fit the job, not vice versa.

These considerations led to the adoption of a modular manipulator architecture. A set of self-contained manipulator modules with standard interfaces provides lower cost and minimizes development time of specialized systems. In addition, modularity allows easy transportation to a remote location, fast on-site assembly, and quick in-the-field repairs. Useful configurations are not limited to manipulators - self-contained actuator modules can be configured into other application-specific mechanisms with fewer or more degrees of freedom.

Some specific mechanical design challenges arising from the modular architecture approach include:

- Mechanical and electrical module interfaces
- Component packaging and wire harness design
- Scalable actuator topologies.

More general mechanical design and engineering goals include:

- Maximum payload to weight ratio and compact design
- High dexterity
- Fault tolerant sensing and actuation
- Fully enclosed mechanisms and wiring
- Accurate joint torque sensing.

Design issues specific to the control of a high performance kinematically redundant manipulator include:

- Providing sensing for advanced control techniques
- Redundancy management, including singularity avoidance and configuration (pose) control
- Robustness and fault tolerance.

1. Schilling Development, Davis, CA

2. Kraft Telerobotics Inc., Overland Park, KS

Table 1 summarizes the principal performance goals.

Table 1 Manipulator Performance Goals

Attribute	Target Value	Notes
Length	55 in.	shoulder pitch to toolplate
Weight (1 G)	165 lb.	actual weight - 150 lb.
Max Endpoint Speed	> 40 in./s	for task space moves
Payload Lateral Force	50 lb. 20 lb. 135 lb.	peak - short duration continuous duty at toolplate, fully extended
Dexterity	7 active degrees of freedom	
Repeatability	0.025 in.	
End Effector Support	72 wires	72 to forearm; 40 to toolplate

Another important design objective was to create a system that could operate terrestrially as well as in a microgravity environment. Previous space manipulators were not operational in 1 G and required special equipment for ground testing. Within the financial scope of this effort, the immediate objective was to develop a system that is a reasonable design evolution away from becoming a space-qualified machine.

MANIPULATOR CONFIGURATION

Figure 1 shows the Dexterous Manipulator. This kinematic arrangement of joint modules includes two shoulder modules (azimuth and elevation), an upper arm roll module, an elbow module, and a three joint wrist module. The upper arm roll module allows the plane formed by the upper arm and forearm to rotate, providing capability for manipulator configuration control. Each joint has a large range of motion, providing a large, dexterous workspace. The elbow (joint 4) offset allows the lower arm to fold up against the upper arm, providing excellent manipulator stowage.

JOINT MODULES

Many of the innovative and unique features of the Dexterous Manipulator are apparent in the joint module design. Each module contains motors, sensors, wiring, transmission elements, and structure. Each joint uses exactly the same drivetrain concept, scaled according to that joint's torque requirements. Module interfaces consist of both positive mechanical connection and self-mating electrical connectors held together with simple clamping collars. There are no inter-module electrical connections that the user must make. This quick disconnect design allows the manipulator to be assembled or disassembled in approximately seven minutes. Table 2 shows the pertinent characteristics of each of the module types.

ACTUATORS AND TRANSMISSION

All of the joints use brushless D.C. motors for actuation. The actuator transmissions use spur gear technology with special mesh geometries and materials to obtain high torque capability. The unique drivetrain design uses a parallel topology that eliminates all backlash without gear mesh adjustments. Figure 2 illustrates the basic concept. In each joint, two motors drive a common output member. Under normal operation, one motor acts as the "prime mover",

Table 2 Module Performance Characteristics

Module	Range of Motion (deg)	Weight (lb)	Peak Torque (in-lb)	Peak Speed (deg/s)	Position Resolution (deg)
Shoulder Azim[a]	325	34.5	8000	72	6.25E-4
Shoulder Elev	325	34.5	8000	72	6.25E-4
Upper Arm Roll	717	27.5	4000	91	6.99E-4
Elbow	235	24.5	4000	91	6.99E-4
Wrist Pitch	238	|	1300	150	7.56E-4
Yaw	208	27.5	1300	150	7.56E-4
Roll	340	|	1300	150	5.50E-3

a. The two shoulder modules are identical.

providing the driving torque, while the second motor provides a small bias torque in the opposite sense. The bias torque removes all backlash from the transmission. Backlash remains zero through continued operation and wear, with no special adjustments required. When large torque s are required, the biasing motor reverses and provides additional torque, at the expense of zero backlash operation. The design also provides single fault tolerance to motor or motor driver failures. A joint can continue to operate in a controlled manner (with reduced bandwidth) after such a failure. After the task at hand is completed, a fully functional module can be swapped with the degraded one, which could in turn be repaired off-line. Each motor is also equipped with its own fail-safe brake so that the manipulator can be powered down in any configuration.

SENSORS

Each joint provides absolute joint position, derived joint velocity, and torque sensing for servo control, as well as motor winding temperature sensing for safety monitoring.

The joint position sensing scheme uses two sensors for each joint. The current manipulator design uses a potentiometer and a brushless resolver. Both are geared to the joint output using precision anti-backlash gears. These devices operate in a "two-speed" mode, providing much higher resolution than can be obtained from either one individually. In addition, the dual sensing scheme provides recovery from single point failures. If the resolver fails, the potentiometer can provide joint position feedback, with reduced servo bandwidth to compensate for the reduced resolution. If the potentiometer fails, the joint can continue to operate normally until the next power cycle, when the absolute joint position must be determined.

The output member of each joint includes special structures instrumented with strain gauges such that joint axis torque measurements can be obtained. The strain gauge signals are amplified using a full bridge amplifier circuit that resides within the joint module. The joint torque information can be used for advanced control techniques such as force reflection or joint torque servoing.

The manipulator wire harness includes dedicated lines to support end effectors or sensors. A single D-connector at the toolplate provides 40 wires. These lines originate in an electronics enclosure, where they can interface with end effector controllers or sensor processing electronics.

CONTROL SYSTEM

The manipulator is controlled by a hierarchical multiprocessor controller that uses advanced control algorithms for high level dexterous motion control and low level joint servo control. The control computer is VME bus-based. It uses three 680x0 family processors along with various data acquisition, memory, and communications devices. The embedded control, or "target" system is linked via Ethernet to a Sun workstation, which serves as the host computer for the graphical user interface. All of the system software is written in the C language and executes on the target system under the VxWorks real time operating system. As future generations of higher-performance hardware and new control techniques become available, this architecture simplifies the evolution process and lengthens the system's technological life.

Manipulator control algorithms include an endpoint control algorithm for task space commands and redundancy resolution, and joint level servo algorithms for tracking the high level commands. The endpoint control algorithm transforms workspace setpoints into joint angle commands while resolving the single redundant degree of freedom. The algorithm provides a "position to position" solution for the joint angle commands, rather than a "rate to rate" pseudoinverse solution with its inherent drawbacks [6]. Options for using the redundancy include manipulator configuration optimization, joint limit avoidance, and singularity avoidance. These criteria may be balanced against one another by setting simple numerical weights that are available through the user interface. Configuration optimization enables the user to specify the manipulator "pose" as well as its tool position and orientation. For example, the user could manipulate in a constrained area by commanding an "elbow down" pose when reaching under an obstacle, or by requiring that the "arm plane" (formed by the upper arm and forearm links) remain horizontal while reaching through a horizontal opening. By specifying the manipulator configuration in addition to the endpoint position, the manipulator motion has the "cyclicity" property - closed endpoint/configuration trajectories have corresponding closed joint space trajectories [6].

Joint level servo algorithms employ a combination of conventional linear control techniques along with advanced nonlinear methods. Feedback loop gains are parameterized by effective joint inertias, which helps to maintain constant joint servo bandwidth throughout the workspace. Additional feedforward terms compensate for gravity loading and manipulator inertia, reducing the required feedback loop bandwidth.

The control system includes safety features to protect the manipulator from error conditions and hardware failures. A "watchdog" process constantly checks sensor signals, algorithm calculations, and computer hardware and stops manipulator motion if it detects any error conditions. The inherent fault tolerance of the actuator and sensor systems makes it unlikely that common types of hardware failures will leave the manipulator marooned.

The graphical user interface enables the user to specify motion trajectories, set algorithm parameters, and determine the manipulator status. As the user selects various operating modes, such as endpoint motion, single joint motion, or playback, different control panels are displayed. These panels enable the user to set motion parameters as well as start and stop the manipulator. For example, the user can define a trajectory using the current manipulator position as the origin. Endpoint trajectories can be defined with respect to different coordinate frames, such as the base or toolplate frames. The user can command both new endpoint or joint trajectories, or replay trajectories stored in a file. The control system enables various algorithm parameters to be changed "on the fly" so that the redundancy resolution criteria and manipulator response characteristics can be modified in real time.

One of the software design's most important features is the interface definition which simplifies modifications and extensions to the control system. Critical data, such as sensor values and motion commands, is accessible from shared memory via simple function calls, greatly simplifying the process of adding new software modules which must use this data. While a commercial end user may not require such low level interaction with the control system, a researcher investigating advanced control algorithms would demand such access. The shared memory architecture provides this access. In fact, the researcher could write modules of C code to implement his algorithms, making the appropriate function calls to access sensor data such as joint angles and rates, compile and link these modules with the rest of the control system software, and evaluate the results using the actual manipulator. As an example, bilateral teleoperator control with a force reflecting master controller could be added by writing a software module that simply

makes the appropriate function calls to place master commands into the manipulator endpoint command memory space. In the same way, endpoint forces could be calculated from the sensed joint torques and transmitted back to the master's computing node.

Odetics has developed and continues to develop advanced control techniques, algorithms, and software for manipulators. In addition to the endpoint and configuration optimization algorithms developed with this manipulator, the company has previously developed algorithms for dual coordinated manipulator control with collision avoidance capability. Path planning and trajectory generation algorithms are currently being developed for the Dexterous Manipulator. The path planning algorithms will find the shortest path around obstacles in the manipulator workspace to a goal position for the manipulator end effector. The trajectory generations algorithms use a potential field approach to guide the end effector along this path while simultaneously avoiding collisions between the end effector, the links of the manipulator, and obstacles in the manipulator workspace. The resulting trajectory can be converted to joint angle commands and input to the joint servo control algorithms.

APPLICATIONS

This manipulator is targeted to address applications which, in addition to dexterity, require the strength and force control of a hydraulic manipulator, but for which hydraulic systems are impractical or impossible. A key member of this class is space manipulators. Many of the initial implementation's sizing and fault tolerance characteristics are chosen to be consistent with space applications. Some potential space applications include satellite servicing operations and truss assembly. A second member of this class is handling of hazardous materials in unstructured terrestrial environments. The manipulator workspace and payload have been chosen sufficiently robust to support both single and dual arm applications. Specific applications in this area include site characterization, radioactive waste handling, and hazardous materials disposal. The manipulator is suitable for tasks such as dexterously positioning and pointing a sensor or handling and transporting cannisters weighing up to 50 pounds.

As industry continues to shift towards a batch-oriented, flexible manufacturing paradigm, the ability to modify production equipment quickly and inexpensively will become increasingly important. As discussed earlier, the structure of this system's hardware and software are highly modular, and will support a wide range of applications that differ substantially from the present seven degree of freedom manipulator. The benefits of system fault tolerance, high precision, and high torque capability can be realized in applications with significantly fewer degrees of freedom, or conversely, in even more complex kinematic configurations. For example, an automated manufacturing operation could require that a tool be pointed accurately under high load, perhaps in an environment with coolant spray or chips. An alternative to custom-designed "hard automation" could be a two module pointing unit. This unit could readily provide the required motion control and load capability, with the added benefit of fault tolerance and very fast change-out if a failure occurs.

COMPARISON TO ROBOTICS RESEARCH MANIPULATORS

As mentioned in the introduction, the commercially available manipulator closest in configuration and performance to the Dexterous Manipulator comes from the Robotics Research Corp. line of modular dexterous manipulators. The K/B-1207 model has a 47.25 inch reach, 20 lb continuous duty payload, and 160 lb. weight, compared to the Dexterous Manipulator's 55 inch reach, 25 lb. continuous payload, and 150 lb. weight. Similarities between the manipulators include electric actuation, joint torque sensing/control, and hierarchical control system implementation. There are also several important differences between the manipulators.

Perhaps the most tangible difference between the systems is that the Robotics Research manipulators have been marketed as commercial products: units have been delivered and installed at various sites. The Dexterous Manipulator described in this paper is a prototype unit. There are important design and implementation differences as well:

1. The most salient design difference is the Dexterous Manipulator's actuator topology that provides fault tolerant sensing and actuation, enhancing the benefits gained from modularity. In particular, fault tolerance would appear mandatory in space and hazardous terrestrial applications where human intervention is extremely undesirable.
2. The actuator reduction methods are different - the Robotics Research joint modules use harmonic drives, while the Dexterous Manipulator uses spur gears exclusively. This reduction method combined with the unique actuator topology provides zero backlash over the life of the mechanism, with no adjustments required. The reduction method also provides somewhat higher forward and backdriving efficiency than harmonic drives.
3. The Dexterous Manipulator module interfaces completely enclose and protect the internal joint components, leaving only D connectors (which are mounted in the joint module flanges) exposed. There are no loose wires to connect during the mating process. These design features contribute to achieving "painless" modularity.
4. The 7 degree of freedom manipulator configurations are somewhat different kinematically. In addition, with its 6.5 inch diameter shoulder module and very smooth exterior lines, the Dexterous Manipulator is extremely compact.
5. The controller architecture and hardware are different - The Robotics Research controller uses both analog and digital control loops. The control computer is Multibus based and uses Intel 80X86 processors. The Dexterous Manipulator controller uses all digital control loops. Its computer is VME bus based and uses Motorola 680X0 processors. The completely digital implementation, VME hardware, and open architecture enhance the control system's adaptability and make it a particularly attractive research tool.

SUMMARY

Odetics has developed a modular Dexterous Manipulator that can be reconfigured for various tasks. The control system algorithms and software have been developed concurrently, yielding an integrated system. Although not currently space qualified, the system design and performance features make it suitable for both space and terrestrial applications. Potential space applications include satellite servicing and refueling, space truss assembly, and Space Exploration Initiative support operations. Terrestrial applications for the 7 degree of freedom manipulator configuration include hazardous material handling in unstructured environments, while reduced degree of freedom configurations could be useful in situations requiring high torque, fault tolerant, and accurate motion components for industrial processes.

In addition to the manipulator, the company is currently developing complementary systems, such as multi-fingered end effectors, a 7 degree of freedom exoskeleton master controller, and advanced control techniques for path planning and collision avoidance. These components can be integrated into complete systems that have the potential to greatly extend the capability envelope of robotic manipulators.

ACKNOWLEDGMENT

The research described in this paper was partially carried out by the Jet Propulsion Laboratory, California Institute of Aeronautics and Space Administration.

REFERENCES

[1] Andary, J.F., Hewitt, D.R., Hinkal, S.W., "The Flight Telerobotic Servicer Tinman Concept: System Design Drivers and Task Analysis", Proceedings of the NASA Conference on Space Telerobotics", January, 1989, pp. 447-471

[2] Herndon, J.N., Babcock, S.M., Butler, P.L., Costello, H.M., Glassell, R.L., Kress, R.L., Kuban, D.P., Rowe, J.C., Williams, D.M, "The Laboratory Telerobotic Manipulator Program", Proceedings of the NASA Conference on Space Telerobotics", January, 1989, pp. 385-393

[3] Wu, E., Diftler, M., Hwang, J., "A Fault Tolerant Joint Drive System for the Space Shuttle Remote Manipulator System", Proceedings of the 1991 IEEE International Conference on Robotics and Automation, Sacramento, CA, April, 1991, pp. 2504-2509

[4] Jacobsen, S.C., Smith, S.M., Backman, D.K., Iversen, E.K., "High Performance, High Dexterity, Force Reflective Teleoperator II", Proceedings of the Fourth ANS Topical Meeting on Robotics and Remote Systems, Albuquerque, NM, February 24-27, 1991, pp. 393-402

[5] Karlen., J.P., Thompson, J.M., Farrell, J.D., "Design and Control of Modular, Kinematically Redundant Manipulators", Second AIAA / NASA / USAF Symposium on Automation, Robotics, and Advanced Computing for the National Space Program, March 9-11, 1987, Arlington, VA

[6] Baillieul, J., "Kinematic Programming Alternatives For Redundant Manipulators", IEEE International Conference on Robotics and Automation, St. Louis, MO, 1985, pp. 722-728

Figure 1 **The Odetics Dexterous Manipulator**

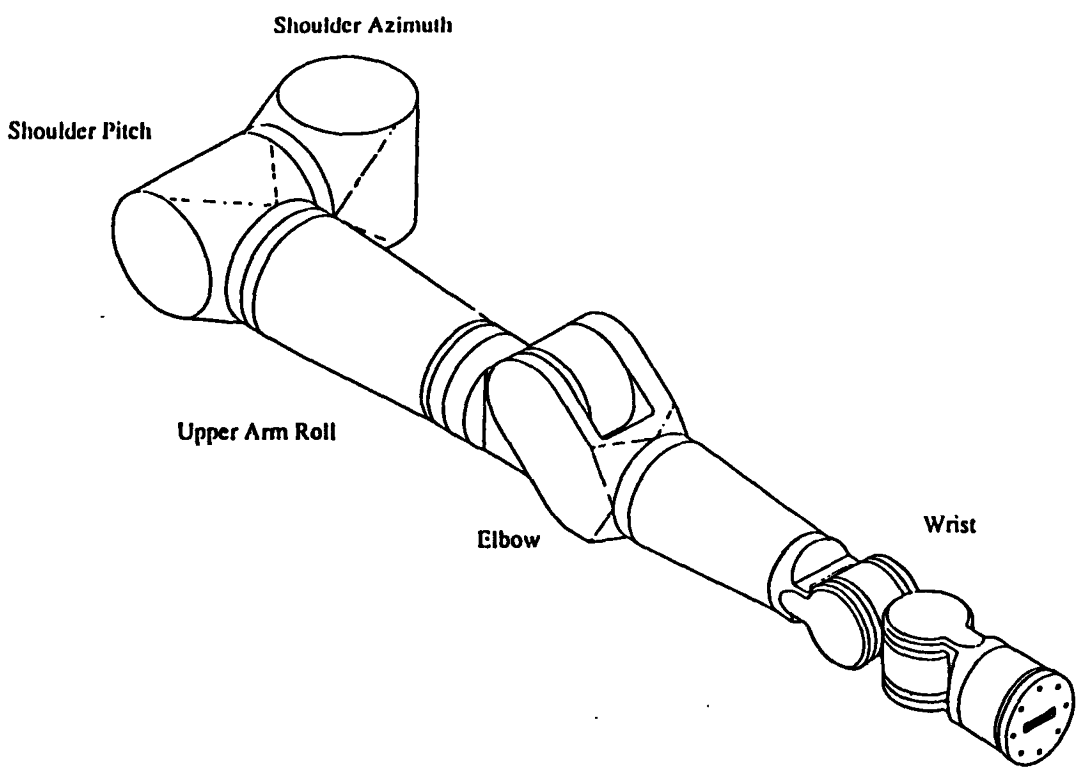

Figure 2 **Dual Motor Drive Concept**